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# FUNDAMENTAL COMBUSTION STUDIES

# RELATED TO AIR-BREATHING PROPULSION

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## FINAL SCIENTIFIC REPORT

Results of this four-year research effort are documented in the thirteen publications listed in the bibliography. These publications may be divided into seven categories which form the subsections of the present report. These categories have been chosen to be consistent with the overall objective of the research.

The overall objective has been to develop further basic knowledge in combustion that will be useful for improving efficiencies and operating characteristics of propulsion systems. Insufficient understanding of the basic mechanisms and processes involved in advanced air breathing combustors, lack of realistic guidelines for predicting characteristics of propulsion devices and of external burning, and a deficiency in methods of combustor design with acceptable pollutant emissions motivated the initiation of this research on advancing understanding of the combustion of fuels in air.

## 1. Ignition Theory

Publications 1 and 2 in the bibliography pertain to the theory of ignition by a hot surface. The problem arises, for example, in the penetration of a fuel tank by a hot object. Since it is impractical to perform numerical integrations of partial differential equations for all cases of interest, the objective has been to develop analytical methods that provide formulas for ignition times that can be used under very wide ranges of conditions. The method adapted was asymptotic analysis for large values of a parameter measuring the sensitivity of the reaction rate to temperature. Although the problem is particularly difficult, it was solved successfully for a wide variety of situations, including taking into account influences of reactant depletion, of Lewis numbers differing from unity and of catalytic behavior of the ignition body. The results are formulas and graphs for ignition times that may be used in parctice.

## 2. Asymptotic Methods in Combustion

Publications 3 and 6 in the bibliography address asymptotic methods in combustion theory. These methods are becoming increasing popular among the theoreticians who are concerned with obtaining results that can be used in practice over broad ranges of conditions. They are especially well suited to providing significant simplifications to the complex problems of combustion. They were employed in the ignition problems discussed above and also extensively in laminar flame theory.[3] Problems of ignition, extinction, turbulent flames, cellular flames and pulsating flames are among those that have been clarified by asymptotic methods.[6] The most useful asymptotic approach has proven to be the so-called activation-energy asymptotics, in which a nondimensional measure of the sensitivity of the heat-release rate to temperature is treated as a large parameter.[6] However, there are a number of other parameters as well to which asymptotic approaches may fruitfully be applied.[6] Appreciable progress has been made along these lines.[6]

## 3. Combustion of Droplets and of Carbonaceous Particles

Publication 5 concerns an experimental and theoretical study of the combustion of small particles of carbonaceous materials. Combustion processes involving droplets and carbonaceous particles occur often in practical combustion chambers, and better understanding of the burning mechanisms can contribute to improved combustor design. The work performed herein involved single particles in the submillimeter size range with emphasis on describing burning rates and extinction conditions. The latter are particularly important for calculating emissions from combustors. The approach has been largely experimental and directed partially toward ascertaining limitations of experimental methods for investigating particle and droplet combustion. Photographic and spectroscopic methods were developed. Burning mechanisms of carbonaceous particles were clarified experimentally.[5]

## 4. Theory of Turbulent Duct Flow

Turbulent combustion is so complex that most of the basic theoretical work in the subject has been restricted to flows in which boundaries do not produce important influences. As a first step toward accounting for effects of boundaries, an analysis was completed of a nonreacting turbulent flow under confinement. This work is reported in publication 4. Matched asymptotic expansions were used to describe turbulent Couette-Poiseuille flow (plane duct flow with a pressure gradient and a moving wall). A special modification of conventional eddy-diffusivity closure accounts for the experimentally observed non-coincidence of the locations of zero shear stress and maximum velocity. An asymptotic solution was developed which is valid as the Reynolds number tends to infinity for the whole family of Couette-Poiseuille flows (adverse, favourable, and zero pressure gradients in combination with a moving wall). It was shown that plane Poiseuille flow is a limiting case of Couette-Poiseuille flow. The solution was shown to agree with experimental data for plane Couette flow, for the limiting plane Poiseuille flow, and for a special case having zero net flow and an adverse pressure gradient. The asymptotic analysis shows that conventional eddy-diffusivity closures are inadequate for general Couette-Poiseuille flows. This result parallels those obtained in studies of turbulent combustion, reported below.

## 5. Theory of Premixed Turbulent Flames

Publications 2, 12 and 13 concern the theory of propagation of premixed flames in turbulent flows having length scales of turbulence large compared with the thickness of a premixed laminar flame. This subject is relevant to combustor design in that, for example, turbulent flame speeds must be known and used properly to obtain efficient designs. Extensive work was completed, providing the first accurate fundamental theory of premixed turbulent flame propagation. This research has revealed many previously unknown properties of premixed turbulent flames and provided a basis for future fundamental investigations in the field.

A statistical theory was developed for the structure and propagation velocity of premixed flames in turbulent flows having scales large compared with the laminar-flame thickness. The analysis, free of usual closure assumptions, involves a regular perturbation for small values of the ratio of laminar-flame thickness to turbulence scale termed the scale ratio, and a singlular perturbation for large values of the nondimensional activation-temperature. The results identify convective-diffusive and reactive-diffusive zones in the flame and predict thickening of the flame by turbulence through streamwise displacement of the reactive-diffusive zone. Profiles for intensities of temperature fluctuations and for streamwise turbulent-transport were obtained. A fundamental quantity occurring in the analysis is the longitudinal displacement of the reactive-diffusive zone in an Eulerian frame by turbulent fluctuations, and to first order in the scale ratio this equals the longitudinal displacement of fluid elements in an Eulerian frame by turbulent fluctuations, herein termed simply the Eulerian displacement. To first order in scale ratio it was found that if the Eulerian displacement experiences the same type of statistical nonstationarity as the corresponding Lagrangian displacement, then the diffusion approximation is valid for streamwise turbulent-transport, but the turbulent flame thickens as time increases, while if the Eulerian displacement is statistically stationary then the diffusion approximation would necessitate a negative coefficient of diffusion in part of the flame, but the flame thickness remains constant. By carrying the analysis to second order in the scale ratio it was shown that the turbulent flame speed exceeds the laminar flame speed by an amount proporational to the mean-square value of the transverse gradient of the Eulerian displacement. This result can be understood from the mechanistic viewpoint of a wrinkled laminar flame in terms of the increase of flame area produced by turbulence. Thus, the theory provides a precise, statistical quantification of the model of the wrinkled laminar flame for describing structures of turbulent flames.

To study effects of flow inhomogeneities on the dynamics of laminar flamelets in turbulent flames, with account taken of influences of the gas expansion produced by heat release, this theory was extended by eliminating the hypothesis of negligible expansion and by adding the postulate of weak-intensity turbulence. The consideration of thermal expansion motivated the formal introduction of multiple-scale methods, which will be useful in sebsequent investigations of influences of hydrodynamic instabilities and of flamelet extinctions. Although the hydrodynamic instability mechanism of Landau was not considered, no restriction was imposed on the density change across the flame front, and the additional transverse convection correspondingly induced by the tilted front was described. By allowing the heat-to-reactant diffusivity ratio to differ slightly from unity, clarification was achieved of effects of phenomena such as flame stretch and the flame relaxation mechanism traceable to transverse diffusive processes associated with flame-front curvature. By carrying the analysis to second order in the ratio of the laminar flame thickness to the turbulence scale, an equation for evolution of the flame front was derived, containing influences of transverse convection, flame relaxation and stretch. This equation explains anomalies recently observed at low frequencies in experimental data on power spectra of velocity fluctuations in turbulent flames. It also shows that, concerning the diffusive stability properties of the laminar flame, the density change across the flame thickness produces a shift of the stability limits from those obtained in the purely diffusive-thermal model. At this second order, the turbulent correction to the flame speed involves only the mean area increase produced by wrinkling. The analysis was carried to the fourth order to demonstrate the mean stretch and mean curvature effects on the flame speed that occur if the diffusivity ratio differs from unity.

These studies have opened the door for obtaining realistic descriptions of premixed turbulent flames applicable to combustors of practical interest. They have also demonstrated the fundamental inapplicability of techniques currently employed. Thereby they have changed the most promising direction for investigating premixed turbulent combustion.

## 6. Theory of Turbulent Diffusion Flames

Publications 7 and 8 concern the theory of turbulent diffusion flames. Such theory is needed for describing combustion in nonpremixed systems. An approach has been available, based on identification of a conserved scaler, for describing turbulent diffusion flames accurately if complete chemical equilibrium is maintained everywhere. This does not always occur in practical combustors, and the present work has been focused on accounting for effects of finite-rate chemistry. These effects produce many practically important phenomena, such as lift-off and blow-off of turbulent-jet diffusion flames.

To describe lift-off and blow-off, a turbulent diffusion flame close to extinction was regarded as an ensemble of laminar diffusion flamelets that are highly distorted such that flame stretch may locally quench a flamelet. The laminar diffusion flamelets were analyzed in the limit of a large activation energy, and the results of Liñán's analysis of counterflow diffusion flames were used to derive the quenching condition. This was illustrated for an analysis for the case of a distorted laminar mixing layer. By analysis of premixed flame propagation in an inhomogeneous mixture it was found that flame propagation occurs close to extinction only along the surfaces of stoichiometric mixture. Thus it was concluded that reaction other than in the diffusion flamelets can be excluded and that the turbulent mean reaction-rate can be expressed as a function of a conditioned-mean scalar dissipation rate. Conditions for blow-off were derived from these results by using the theory of conduction in randomly distributed networks, commonly termed percolation theory. The connection between percolation theory and diffusion-flame theory unites two large and previously entirely diverse areas of applied physics.

Further work has shown that the theory developed for diffusion-flame lift-off provides results for lift-off heights in reasonable agreement with experimental data. A fundamentally justified view of lift-off thereby has been developed that differs completely from previously accepted descriptions of the process.

7. General Approaches to the Theory of Turbulent Combustion

As part of this work, overall appraisals were made of the current status of theories of turbulent combustion, with emphasis on ascertaining what can and cannot be calculated with confidence in turbulent combustion. These appraisals appear in publications 9 and 10. These publications deliniate regimes of turbulence in which combustion predictions can be made reasonably and others in which they cannot. The work thus has resulted in a detailed evaluation of the status of the field.

## CONCLUSIONS

This research has advanced our abilities to describe reacting flows in a number of respects. Especially notable are the accomplishments in premixed turbulent flame theory, in the theory for lift-off and for blow-off of diffusion flames, and in ignition theory. The results may be used for improved analysis and design of combustors.

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